Implications of muon anomalous magnetic moment for supersymmetric dark matter

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The anomalous magnetic moment of the muon has recently been measured to be in conflict with the Standard Model prediction with an excess of 2.6σ. Taking the excess at face value as a measurement of the supersymmetric contribution, we find that at 95% confidence level it imposes an upper bound of 500 GeV on the neutralino mass and forbids higgsinos as being the bulk of cold dark matter. Other implications for the astrophysical detection of neutralinos include: an accessible minimum direct detection rate, lower bounds on the indirect detection rate of neutrinos from the Sun and the Earth, and a suppression of the intensity of gamma ray lines from neutralino annihilations in the galactic halo.

95.35.+d, 14.80.Ly, 95.85.Pw, 95.85.Ry, 98.70.Rz

Recently, the Brookhaven AGS experiment 821 measured the anomalous magnetic moment of the muon $a_\mu = (g-2)/2$ with three times higher accuracy than it was previously known [1]. Their result is higher than the Standard Model prediction at greater than 2.6σ. One well-known possibility is that supersymmetric corrections to a_μ are responsible for this discrepancy [2–4]. In this Letter, we take the approach that all the measured discrepancy is due to supersymmetric contributions, and discuss the implications of this measurement for searches of neutralino dark matter.

There are two caveats to our approach. The first is that there is some disagreement on what the Standard Model prediction is, primarily in the hadronic contribution. There remain theoretical evaluations for which the new experimental result agrees with the Standard Model [5]. The second caveat is that supersymmetry is only one possibility for physics beyond the Standard Model that could contribute to a_μ. Other possibilities include (but are not limited to) radiative fermion masses, extended technicolor and anomalous gauge boson couplings, as summarized in Ref. [4].

The lightest stable supersymmetric particle in the Minimal Supersymmetric Standard Model (MSSM) is most often the lightest of the neutralinos, which are superpositions of the superpartners of the neutral gauge and Higgs bosons,

$$\tilde{\chi}^0_1 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}^0_1 + N_{14}\tilde{H}^0_2. \qquad (1)$$

For many values of the MSSM parameter space, the relic density $\Omega_\chi h^2$ of the (lightest) neutralino is of the right order of magnitude for the neutralino to constitute at least a part, if not all, of the dark matter in the Universe (for a review see Ref. [6]). Here Ω_χ is the density in units of the critical density and h is the present Hubble constant in units of 100 km s^{-1} Mpc^{-1}. Present observations favor $h = 0.7 \pm 0.1$, and a total matter density $\Omega_M = 0.3 \pm 0.1$, of which baryons contribute roughly $\Omega_b h^2 \approx 0.02$ [7]. Thus we take the range $0.052 \le \Omega_\chi h^2 \le 0.236$ as the cosmologically interesting region. We are also interested in models where neutralinos are not the only component of dark matter, so we also separately consider models with arbitrarily small $\Omega_\chi h^2 < 0.236$.

Parameter	μ	M_2	$\tan\beta$	m_A	m_0	A_b/m_0	A_t/m_0
Unit	GeV	GeV	1	GeV	GeV	1	1
Min	-50000	-50000	1.0	0	100	-3	-3
Max	50000	50000	60.0	10000	30000	3	3

TABLE I. The ranges of parameter values used in the MSSM scans of Refs. [8,9,11–13]. In this Letter, we use approximately 79,000 models that were not excluded by accelerator constraints before the recent a_μ measurement.

We have explored a variation of the MSSM. Our framework has seven free parameters: the higgsino mass parameter μ, the gaugino mass parameter M_2, the ratio of the Higgs vacuum expectation values $\tan\beta$, the mass of the CP–odd Higgs boson m_A, the scalar mass parameter m_0 and the trilinear soft SUSY–breaking parameters A_b and A_t for third generation squarks. Our framework is more general than the supergravity framework, in that we do not impose radiative electroweak symmetry breaking nor GUT unification of the scalar masses and trilinear couplings. The only constraint from supergravity that we impose is gaugino mass unification, though the relaxation of this constraint would not significantly alter our results. We assume that R-parity is conserved, stabilizing the lightest superpartner. (For a more detailed description of the models we use, see Refs. [8–10].)

As a scan in MSSM parameter space, we have used the database of MSSM models built in Refs. [8,9,11–13]. The overall ranges of the seven MSSM parameters are given in Table I. The database embodies one–loop corrections for

the neutralino and chargino masses as given in Ref. [14], and leading log two–loop radiative corrections for the Higgs boson masses as given in Ref. [15]. The database contains a table of neutralino–nucleon cross sections and expected detection rates for a variety of neutralino dark matter searches.

The database also includes the relic density of neutralinos $\Omega_\chi h^2$. The relic density calculation in the database is based on Refs. [9,16] and includes resonant annihilations, threshold effects, finite widths of unstable particles, all two–body tree–level annihilation channels of neutralinos, and coannihilation processes between all neutralinos and charginos.

We examined each model in the database to see if it is excluded by the most recent accelerator constraints. The most important of these are the LEP bounds [17] on the lightest chargino mass ($m_{\chi_1^+} > 88.4$ GeV for $|m_{\chi_1^+} - m_{\chi_1^0}| > 3$ GeV and $m_{\chi_1^+} > 67.7$ GeV otherwise) and on the lightest Higgs boson mass m_h (which ranges from 91.5–112 GeV depending on $\tan\beta$) and the constraints from $b \to s\gamma$ [18] (we used the LO implementation in DarkSUSY [19]).

The results of Brookhaven AGS experiment E821 [1] for the anomalous magnetic moment of the muon, $a_\mu = (g-2)/2$, compared with the predicted Standard Model value are

$$a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM}) = (43 \pm 16) \times 10^{-10}. \qquad (2)$$

This represents an excess of 2.6σ from the standard model value given in Ref. [4].

The anomalous magnetic moment a_μ is quite sensitive to supersymmetry, as has been calculated by several authors [2–4]. Supersymmetric corrections to a_μ, $\Delta a_\mu(\mathrm{SUSY})$, can be either positive or negative, so in significantly reducing the errors in the measurement of a_μ, models with negative $\Delta a_\mu(\mathrm{SUSY})$ can be ruled out at high confidence.

We assume that the entire discrepancy (Eq.2) is made up by supersymmetric corrections, and investigate the implications for the MSSM parameter space. We consider a 95% (2σ) confidence region for the supersymmetric contribution, accepting the following range of $\Delta a_\mu(\mathrm{SUSY})$

$$10 \times 10^{-10} \leq \Delta a_\mu(\mathrm{SUSY}) \leq 75 \times 10^{-10}. \qquad (3)$$

We compute $\Delta a_\mu(\mathrm{SUSY})$ for the models in the database using the full calculation in Ref. [3].

In Fig. 1 we plot the ratio of gaugino and higgsino fractions against the mass for the lightest neutralino in a large sample of models. This ratio is defined as

$$\frac{Z_g}{1-Z_g} = \frac{|N_{11}|^2 + |N_{12}|^2}{|N_{13}|^2 + |N_{14}|^2}. \qquad (4)$$

We show the allowed region, with and without the new constraint on $\Delta a_\mu(\mathrm{SUSY})$, in two cosmological cases. On the left, we only require that $\Omega_\chi h^2 < 0.236$, whereas on the right, we consider models where the dark matter could be entirely neutralinos, with the previously mentioned cosmologically interesting range for $\Omega_\chi h^2$. In both cases, models allowed before the $\Delta a_\mu(\mathrm{SUSY})$ constraint are plotted as crosses, and models respecting the $\Delta a_\mu(\mathrm{SUSY})$ constraint are plotted as crossed circles.

The most pronounced effect of applying the $\Delta a_\mu(\mathrm{SUSY})$ bound is an upper limit of 500 GeV on the neutralino mass. The previous bound of 7 TeV was cosmological, that is from the constraint $\Omega_\chi h^2 < 1$ [9]. We now find that the bound from $\Delta a_\mu(\mathrm{SUSY})$ on the neutralino mass is significantly more stringent. We note, however, that in taking the 3σ range of the experiment, the Standard Model value is included, and the new bound is completely removed.

Another interesting effect of applying the $\Delta a_\mu(\mathrm{SUSY})$ bound appears when we impose that the neutralino constitutes the bulk of cold dark matter ($0.052 \leq \Omega_\chi h^2 \leq 0.236$). In this case, the neutralino must have at least a 10% admixture of gauginos. Therefore, we can make the claim that neutralino dark matter can not be very purely higgsino-like. The experimental bound on $\Delta a_\mu(\mathrm{SUSY})$ disfavors higgsino dark matter even without the theoretical assumption of supergravity.

We now discuss the implications of these new constraints for astrophysical searches for neutralino dark matter.

One of the most promising astrophysical techniques for detecting neutralino dark matter is the so-called direct detection program. Neutralinos in the galactic halo are constantly passing through the Earth, and may be detectable with sensitive underground instruments such as CDMS [20] and DAMA [21]. The neutralino–nucleon elastic scattering cross section is correlated with $\Delta a_\mu(\mathrm{SUSY})$ [22]. In the top left panel of Fig. 2, we plot the spin-independent neutralino-proton scattering cross section. The constraint due to $\Delta a_\mu(\mathrm{SUSY})$ is intriguing, as it raises the minimum cross section by many orders of magnitude, to around 10^{-9} pb. This is very interesting in that it places a bound that is conceivably detectable in future experiments, such as GENIUS [23].

Another possible method to detect neutralino dark matter is neutrino telescopes, such as at Lake Baikal [24], Super-Kamiokande [25], in the Mediterranean [26], and the south pole [27]. Neutralinos in the galactic halo undergo scatterings into bound orbits around the Earth and Sun, and subsequently sink to the centers of these bodies. The resulting enhanced density can produce a detectable annihilation signal in neutrinos at GeV and higher energies. The detectability of this signal is strongly correlated with the capture rate, which in turn is strongly correlated with the neutralino-nucleon cross sections discussed in the previous paragraph. Thus, there is a much more promising lower bound on the neutrino flux from the Sun, though the flux from the Earth can still be quite small. To illustrate, we plot the rate of neutrino-induced through-going muons from the Sun, along with the unsubtractable background, in the top right panel of Fig. 2.

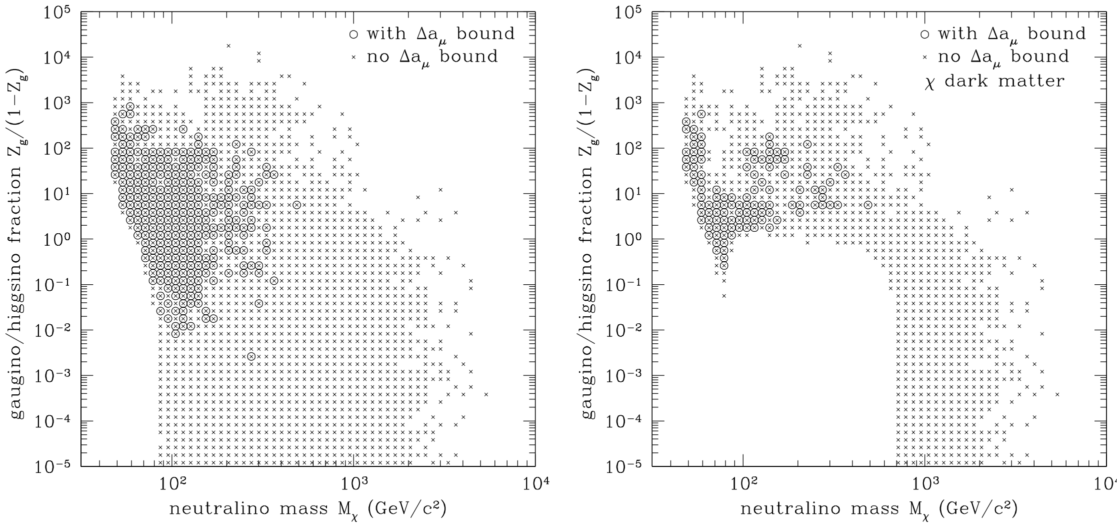

FIG. 1. Gaugino/higgsino fraction versus mass for the lightest neutralino. In the left panel, we plot our set of models allowed by cosmology, but not requiring that Ω_χ be large enough to account for the dark matter. In the right panel, we apply the constraint that the dark matter is neutralinos, as discussed in the text. Crosses indicate previously allowed models, and the crossed circles indicate models allowed after imposing the Δa_μ(SUSY) bound.

We see that the Δa_μ(SUSY) bound removes most undetectable models, though there remain some such models at low neutralino masses, as they suffer from threshold effects [12]. The flux of neutrinos from the Earth is plotted in the bottom right panel.

Gamma ray experiments such as atmospheric Čerenkov telescopes (ACTs) can in principle detect the annihilation lines of dark matter neutralinos in the galactic halo directly either to two photons, or to a photon and a Z boson. In removing the high-mass models, the reach of ACTs is limited, as they tend to have thresholds above 100 GeV [11]. Furthermore, we see that applying the Δa_μ(SUSY) bound (bottom right panel of Fig. 2) does not greatly increase the lower bound of gamma ray flux.

In this Letter we have discussed some implications of the recent measurement of the anomalous magnetic moment of the muon [1]. In particular, we have shown that in taking the measurement at face value, the constraints placed on the supersymmetric parameter space significantly improve the prospects for direct detection experiments seeking to measure the infrequent scatterings of galactic halo neutralinos and neutrino telescopes seeking the annihilation signals from the centers of the Earth and Sun. Searches for the monochromatic gamma rays from neutralino annihilation towards the galactic center are not helped or hindered much by this result.

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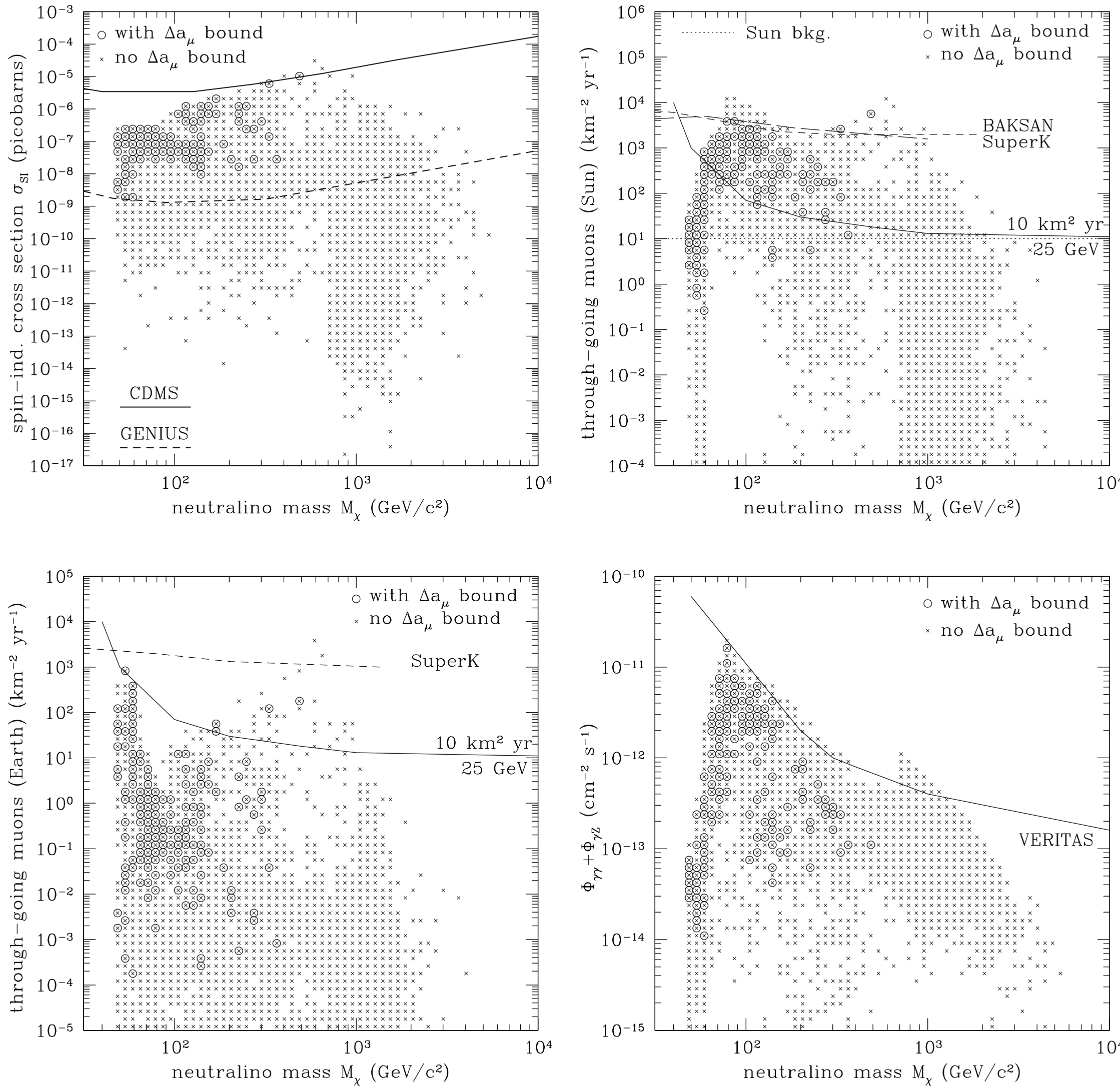

FIG. 2. Astrophysical detectability of SUSY models. In all plots, small crosses indicate cosmologically interesting models, and crossed circles indicate such models that pass the Δa_μ(SUSY) cut. In the top left we plot the spin-independent cross section for neutralino-proton scattering, combined with the CDMS bound and the reach of GENIUS. In the top right we plot the rate of through-going muons in a neutrino telescope for the annihilations in the Sun, with the BAKSAN and SuperKamiokande bounds, and the reach of a km^2 telescope. In the bottom left, we plot a similar rate for neutrinos from the center of the Earth. In the bottom right we plot the intensity of the gamma ray lines in the direction of the galactic center, with the future reach of the VERITAS experiment [28].

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